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Certified Radio-Trician's Course
(REG. U. S. PAT. OFF.)

NRI

INDUCTANCE

No. 6FR

Originators of Home Study Radio Courses
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FOREWORD

The man who has made up his mind to be successful, is already well on the way to success. Determination is the soul of achievement. There are other factors that help to determine a man's future, it is true, but if he has determination to succeed, a real determination, he is like a steam-roller under full steam, nothing can stop him.

Look ahead to the success and happiness that will come to you if you throw yourself, body and soul, behind your determination to succeed. Each lesson well completed is one step taken toward your goal. Give your best to each lesson—make the knowledge contained therein part of you. Learning parrot fashion won't do much good; satisfy yourself that you *understand* everything—then your lesson grades will take care of themselves and you'll have the sort of knowledge you can use.

Of course it isn't going to be easy. It's hard for most people to lay out a plan and stick to it absolutely. But on the other hand, nothing that is easy is worthwhile. You can succeed just as others have—so keep your determination alive. I'm with you.

J. E. SMITH.

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NATIONAL RADIO INSTITUTE WASHINGTON, D. C.

MUTUAL INDUCTION

From what you have learned in the previous lessons of the course, you know that coils are essential for Radio reception—a receiver could not be built without including coils in its construction. The same thing can be said for resistors and condensers. In fact, these three are largely responsible for Radio reception—and not only reception, but transmission as well. Every transmitter and every receiver has resistors of definite values, coils built according to very close specifications, and condensers carefully designed and accurately built.

In the preceding lessons, we studied resistors and the effect of resistance in electrical circuits with particular reference to Radio circuits. We learned that resistance is the *property* of resistors, that some electrical energy is converted into heat energy in a resistor, and that resistance can be used to control voltages—in fact, we now have a very clear idea of resistance, we know how to measure it, and how to connect various resistors together in order to get desired values of resistance.

In this text-book we are going to learn about coils in the same practical manner:—Why coils are used, what property they have that is made use of in Radio, how this property (inductance) affects electric currents, how it is measured, and all about it.

But as so often happens in the study of Radio, we can't start out immediately by studying inductance itself. We must first study the simple electrical effects which are at the bottom of what we know as inductance.

Consider the simple experiment set up in Fig. 1. Here we have two wires, two electrical conductors that is, laid side by side, but not touching each other. To wire AB, a source of direct current is connected which is most likely an electric battery. In the same circuit, is a key, K, connected in series to act as an off-on switch so that we can open or close the circuit at will. We also place in this circuit an ammeter so that we can keep a check on the current flow.

The second wire CD is connected to a sensitive voltmeter, a galvanometer, to form a second circuit. As you see, this voltmeter is of the type which has its zero position in the center of the scale so that it will indicate in which direction current is flowing. Very obviously, there is no direct electrical connection or mechanical connection between these two circuits.

Now let us depress the key, allowing current to flow in circuit No. 1. Watch the voltmeter in circuit No. 2 carefully. At the instant the key is depressed, it will be noted that the voltmeter needle in circuit No. 2 deflects, showing of course that there is a voltage in the circuit. How can this be, since there is no electrical connection between the two circuits?

If we keep circuit No. 1 closed, that is, we don't release the key, we notice that the voltmeter in circuit No. 2 now shows a zero reading—after its first deflection, the needle returns to zero. How can we explain this? If there is a voltage in circuit No. 2 when current begins to flow in circuit No. 1, why shouldn't there be a voltage present as long as there is current flowing in circuit No. 1?

But let us continue our experiments before we stop to explain these peculiar things. We release the key, opening circuit No. 1. Current stops flowing, very naturally. We are watching the voltmeter in circuit No. 2 carefully. And here we notice something else peculiar—at the instant circuit No. 1 is opened, the voltmeter needle deflects, but this time in a direction *opposite to* the direction of the first deflection. This can mean only one thing—that somehow or other, when we released the key, a voltage was again created in circuit No. 2, but that this time the voltage was in a direction opposite to the direction of the first voltage.

Our first conclusion after observing this experiment is that there are evidences of voltage in circuit No. 2 only when current flow in circuit No. 1 is stopping or starting. Can this be explained?

You remember in a previous lesson it was brought out that there was something peculiar about the space surrounding a wire carrying current. We said that about a wire carrying current there are always magnetic lines of force, usually referred to as "flux." And it is because of this flux about the wire in circuit No. 1 that a voltage was created in circuit No. 2. This leads us to the statement of another fundamental principle of electricity and Radio—that when flux *cuts* across a wire, an electrical conductor, or when a conductor cuts through flux, a voltage will be created (induced) in that conductor. Notice, however, that there must be *motion,* either the conductor must be moving and cutting through the flux, or the flux must be in motion before a voltage can be induced.

This explains why there was no reading possible in circuit No. 2, when the current in circuit No. 1 was flowing steadily—the flux was stationary. But when current started to flow in circuit No. 1, the flux about the conductor had to be built up—and as it built up from nothing to maximum it cut across circuit No. 2, inducing in circuit No. 2 a voltage. But just as soon as the flux reached maximum and the continuous current flowing in circuit No. 1 maintained it at maximum, it became stationary, there was no cutting, and consequently no voltage induced.

Then when the current in circuit No. 1 was suddenly cut off, its magnetic field collapsed. This collapse of course constitutes a motion, a movement of flux inward, instead of outward. But that doesn't make any difference, as long as there is a movement. This movement induces another voltage into circuit No. 2 but in the opposite direction, because the flux is now moving toward wire AB instead of away from wire AB. The deflection of the voltmeter needle will show this very clearly.

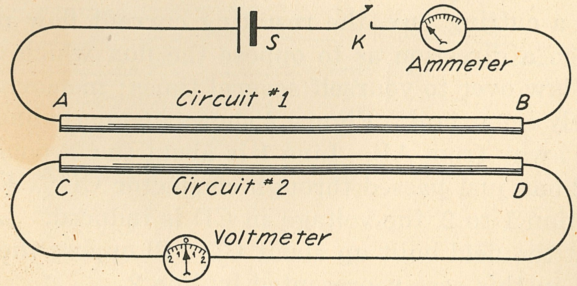


Fig. 1

There are several things of interest in connection with this experiment which must be cleared up before we thoroughly understand everything that happens when a voltage is induced in CD. Does the first current in the wire CD in Fig. 1 flow in the same direction as that in AB?

To make this clear, study carefully Fig. 2 in which the conductors in Fig. 1 are shown in perspective. A current is flowing through AB in the direction shown by the arrow and from our right-hand rule for direction of magnetic field resulting from current flow, we immediately deduce the fact that the magnetic field around AB is in a clockwise direction or as shown in Fig. 2 by the circular lines whose direction is indicated by the arrows.

As the current starts to flow in AB, these magnetic lines of force spread out around the wire AB, moving towards the conductor CD and pass through it. At the instant of passing through the conductor CD, these magnetic lines of force induce a voltage into it, and if this conductor CD is part of a circuit, as it is in Fig. 1, a current will flow. The current in CD naturally produces a magnetic field of its own.

Before we can determine in what direction the current in CD is, we must thoroughly understand the law of magnetic flux action discovered by Lenz, from whom it derives the name "Lenz's Law." This law can be expressed in many ways and one of the ways is as follows—with particular reference to the experiment under question: When a voltage is induced in a conductor by a cutting flux, the resulting current flow produces a flux in such a direction as to oppose the flux which created it. Read this law over to yourself several times; memorize it for it is extremely important. Figure 2 shows magnetic lines of force spreading away from AB. Line 1 is about to cut conductor CD and line 2 has just passed through conductor CD. When going from position 1 to 2, the voltage in CD is induced. Lenz's Law states that the field built up about CD will oppose the field that created it, in this case represented by line 2.

Imagine that a current is flowing in conductor CD in a direction from D to C. From the right-hand rule we can see that the lines of magnetic force would be upward and in the opposite direction to that of line 2. And this is the proper direction for the induced current also according to Lenz's Law.

When current stops flowing in AB, the magnetic field about AB collapses. As it collapses it again cuts across the wire CD and in doing so induces a voltage in the wire CD. Naturally this does not happen until the lines pass through the conductor CD from position 2 to 1, and from Lenz's Law we immediately deduce that the voltage induced in the wire CD must be in a direction opposite to the direction of current flow in the previous experiment.

This leads you to another question and it is a good one, too. When the flux AB collapses, does it have any effect on the wire AB? Yes, indeed; it induces current flow in its own conductor and the flow thus induced will act in the same direction as

the original voltage, tending to prolong current flow in AB after the circuit has been broken at K.

When a voltage is induced in a conductor by its own collapsing field, it is, we say, self-induced and the action is called *self-induction* to distinguish it from mutual induction, the creation of a voltage by magnetic interaction (flux linkage) between two separate conductors.

If a collapsing magnetic field creates an e.m.f. in the conductor about which the field was created, will an e.m.f. be induced in that conductor while the field is being built up? Of course, and this is self-induction just as an e.m.f. was created by self-induction when the field collapsed on itself. According to Lenz's Law, when a current is increasing in a circuit the e.m.f. of self-induction opposes the increase; when a current in a circuit decreases, the e.m.f. of self-induction tends to prevent the decrease. From this it is clear that a collapsing magnetic field will induce a voltage in its conductor, in the same direction as the original voltage.

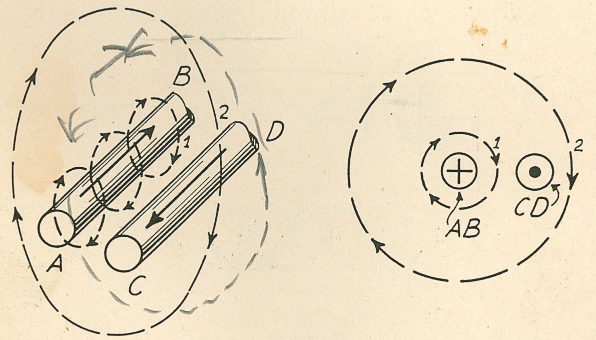


Fig. 2

Now we are ready to go a step further. Let us forget about circuit No. 2 in Fig. 1 and work with circuit No. 1. But instead of leaving it in its present form, let us take conductor AB and wind it on some tubular form, making a small coil as in Fig. 3. We have the same amount of wire, but it is arranged differently. Will this new arrangement have any effect on a current flowing through the circuit? You can answer that question from what you have already learned about self-induction and mutual induction in this lesson, can't you? We know that there is a magnetic field built up about each turn when current begins to flow through the coil. We know that as long as this field keeps moving, in this case, increasing, a counter-e.m.f. will be induced in each turn. But each turn has its own magnetic field which at the instant we are considering it, is *moving* outward from the portion of the conductor about which it is created. Will the flux about turn 1 have any effect on turn 2? Certainly. Between adjacent turns, there is *mutual induction* just as though the two turns were in separate circuits. The increasing flux about 1 will induce a voltage in turn 2. The increasing flux about turn 2 will induce a voltage in 1. There will be the same interlinkage of flux between 2 and 3, and between 3 and 4.

You can see what we are getting at. The total counter-e.m.f. (back e.m.f.) induced in the coil until the flux reaches maximum will be much greater than the back e.m.f. induced in a straight conductor. Of course when the flux is stationary, that is, when it has reached maximum and the current flowing through the coil keeps it at maximum there is no magnetic interaction between turns and there is nothing to prevent the free passage of current through the coil except the resistance of the wire. But suppose we cut off the current, the magnetic fields collapse, inducing in their own turns and adjacent turns, an e.m.f., in the same direction as the original current that created the fields, according to Lenz's Law—and the current tends to keep on flowing for a short time after the source of e.m.f. has been disconnected.

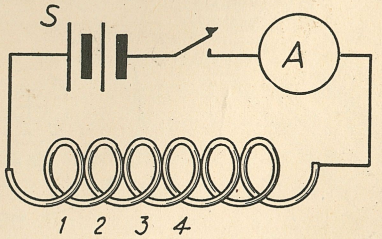
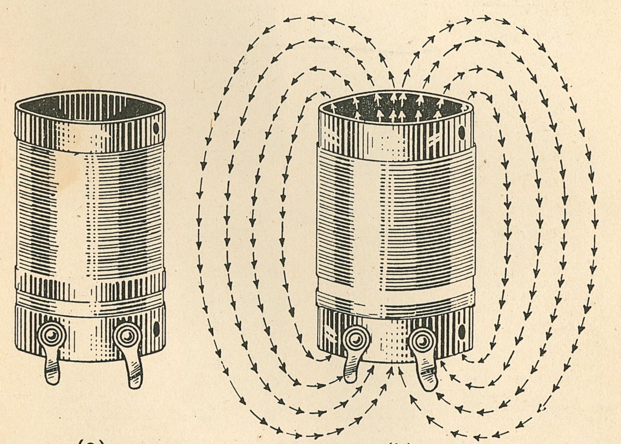


Fig. 3

Now in place of this improvised coil we can place in the circuit the sort of coil we are familiar with in Radio work. Let it be a coil such as shown in Fig. 4(a). The windings are close together, almost touching, so that very little flux can flow between the windings. The result is that all the fields of the individual wires combine to form a complete, single field for the entire coil as shown in Fig. 4(b). We know what effect the coil will have on the current flow—that it will be impeded to some extent, it will be opposed by the counter-e.m.f. induced in its turns by the expanding magnetic field. We know that when the field becomes stationary, the current will flow practically unimpeded. We know that when the key is opened the current will "want" to keep on flowing due to the collapse of the coil's magnetic field. Unfortunately, our ammeter is too slow to indicate the presence of this back e.m.f. but if our coil were large enough, at the instant we opened the circuit, a spark would jump across the key contacts proving that the energy stored in the magnetic field has been reconverted into electrical energy.

INDUCTANCE (L)

The property of a coil which makes it difficult for current to start flowing, and when once flowing to have difficulty in stopping is called *inductance*. The symbol for inductance is always "L." This slowing up of current flow while a magnetic field is being built up about a coil, and the tendency to prolong current flow when the field collapses is the result of the *inductance* of the coil. And inductance includes the effects of self-induction in individual turns and the mutual induction between adjacent turns.



(a) (b)

Fig. 4

Inductance in an electrical circuit is often well compared to mechanical inertia. Every fly wheel provides an example of mechanical inertia. Suppose at normal running speed a heavy fly wheel revolves at 100 revolutions per minute. Is it possible to get it moving at 100 r.p.m. from a dead stop instantly? Of course not—and considerable energy or power is required to get it moving at that speed. After it is moving at this speed, however, less power is required to keep it up to speed. Now, if the driving force is removed, the fly wheel does not come to a stop instantly—in fact, if it is desired to bring it to an instant stop considerable energy must be applied in the opposite direction, in the form of a braking force. We say that the fly wheel in motion has momentum and this momentum must be overcome by some form of resistance before the wheel will stop revolving.

A simple explanation of this is that when we are overcoming the inertia of the fly wheel, which requires more energy than to keep it moving, we are storing energy in the wheel in the form of momentum. When the driving force is removed from the wheel, the energy stored in it is converted into motion. And as soon as all the stored energy is used up, the wheel comes to a stop.

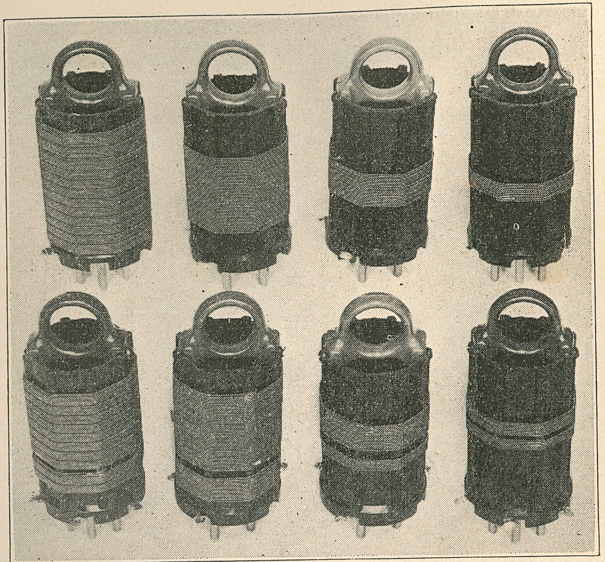


Fig. 5—Typical Radio Plug-in Coils.

The same thing is true if we want to increase speed. To build up the speed we must overcome some more inertia, storing more energy in the form of momentum. When decreasing the speed, the energy stored will tend to keep the wheel moving at the faster speed—until the energy stored has been entirely dissipated by resistance, the resistance at the center bearing and the air resistance.

You can see how close this analogy is. Inductance in a circuit is both inertia and momentum, it tends to prevent current from flowing, and once the current is flowing "at full speed," it tends to keep it flowing even though the driving force (the source of e.m.f.) is removed. Energy is stored in the magnetic field about the coil—when the driving force is removed, the magnetic energy is converted into electrical energy and delivered to the circuit again. Moreover, inductance tends to prevent any change in current flow, whether from a lower to a higher value, or from a higher to a lower value.

There has always been a great deal of confusion in the terminology of this subject. Mutual induction is often called mutual inductance; self-induction, self-inductance. We have been very consistent in this lesson and it should be perfectly clear to you that inductance is the result of self-induction in the turns of a coil and mutual induction between adjacent turns. And inductance is, strictly speaking, the property of coils, not the coil itself, although Radio engineers and Radio-Tricians often speak of a coil as an "inductance." While this is not really correct, it is convenient and is often heard, and seen for that matter, even in text-books.

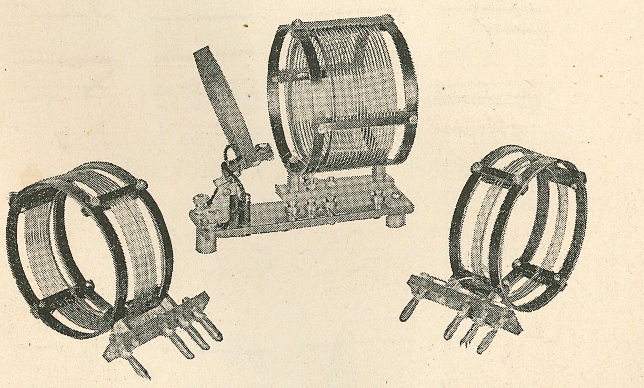


Fig. 6—Short Wave Transmitting and Receiving Plug-in Coils.

In Figs. 5 to 8 are pictured various types of coils used in Radio. The coils in Fig. 5 are typical R.F. coils on plug-in forms so they can easily be interchanged. Figure 6 shows several coils of the types used in short wave transmitters and sometimes in S.W. receivers. The two single coils are plug-in coils and are interchangeable so that the transmitter or receiver can be made to operate on different bands of frequency. The two coils in the center form an inductive coupling device, a subject to which a whole future lesson will be devoted.

A set of typical transmitter coils used for broadcast wavelengths is shown in Fig. 7. In Fig. 8 is shown a set of coils which is used for maintaining various standards of inductance. These coils belong to the U. S. Bureau of Standards.

Enough pictures of coils have been shown to give you an idea of the many different forms they may take. The design of a coil depends primarily on how much inductance it is to have and how much current its windings are to carry. There are other secondary factors that enter into coil design, but consideration of them must be kept for later.

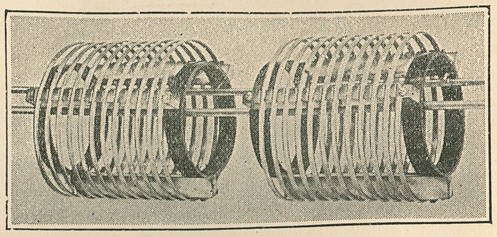


Fig. 7—Broadcast Transmitting Coils.

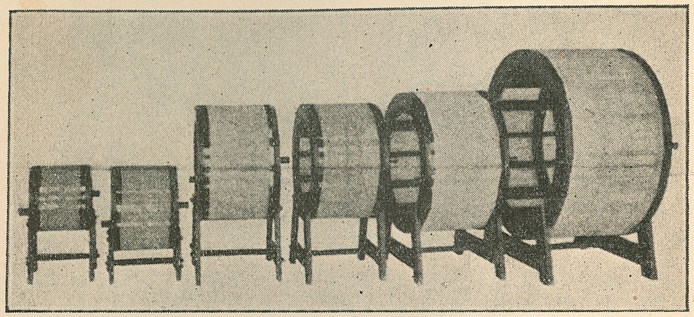


Fig. 8—Single-layer Coils used as standards of inductance.

Coils may be used together, either connected in series or in parallel. If connected in series, their inductances *add* just as the resistances of two resistors in series add. Suppose we have three coils in series—the total inductance will be $L_1 + L_2 + L_3$, provided that there is no magnetic interaction (mutual induction) between coils. If there is mutual induction between coils, the total inductance will be greater or smaller. The total inductance of coils in parallel must be calculated in the same manner as resistance for resistors in parallel. The total inductance L, if

L_1, L_2, and L_3 are in parallel, will be found from the formula

$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}$$

At this point it is necessary to digress for a moment from the subject of inductance. You may have realized before this that a coil cannot be built to have only inductance. No matter what we do, every coil we build will have a certain amount of resistance. We can't get away from the fact that wire has resistance, whether it is straight or coiled. Conversely, every winding has inductance, even though it is intended as a resistance. In wire-wound resistors this inductance must be kept as low as possible, otherwise it will add to the inductance in its circuit and upset the balance of the circuit. For this reason some form of non-inductive winding is often used.

Figure 9(a) will help to make clear the principle underlying non-inductive winding. If a wire is turned back on itself as shown, the magnetic fields of individual turns will be in opposite directions to each other. Consequently even though there will be, theoretically, a counter-e.m.f. induced in each half of the conductor due to mutual induction, the current flowing will not be affected in any way because the induced e.m.f.'s will be equal and opposite, therefore they balance. See Fig. 9(b) for a practical application of this principle—the arrangement of filament feed wires in A. C. receivers to avoid any inductive effects between themselves and other circuits. The conductor shown as EF is close enough to the lead wires to have voltage induced in it by the magnetic flux of AB and CD. Here again we have two voltages induced in EF but as they are opposite, they cancel.

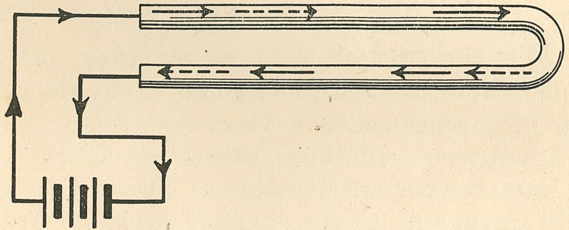


Fig. 9(a)

There is still the very small e.m.f. of self-induction in each conductor opposing the starting and stopping of current, but this can't be helped, any more than we can make wire without resistance.

THE UNITS OF INDUCTANCE

Whenever a coil is made, a certain *amount* of inductance is built into it. The fact that we talk about the amount of inductance, shows that it is quantitative, that is, it can be measured, and the amount of inductance expressed numerically. You remember that resistance is measured in ohms—and the ohm is the unit of resistance. Inductance is measured in henries—the unit of inductance is the henry, so called after Joseph Henry; an American scientist.

Now you want to know just how much inductance one henry is. When a voltage is applied to a coil, the inductance of the coil attempts to keep the current from flowing, that is, there is a self-induced e.m.f. which opposes the applied e.m.f. (for this reason it is often called a back e.m.f.). The greater the back e.m.f. the more difficult will it be for the current to change as the applied voltage changes. If the current increases or decreases at the rate of one ampere per second because of a back e.m.f. of one volt, the coil has an inductance of one henry.

Notice that the current must be changing, otherwise the flux would be stationary and there could be no induced voltage. This change of current could be from 5 amperes to 4 amperes, from 22 to 21 amperes—anything, just so the change would be at the rate of 1 ampere per second of time. It could even be a very small change in current, as for example, a change from 9 to 10 milliamperes. If the inductance is 1 henry, it will take one-thousandth ($\frac{1}{1000}$) of a second for the current to change 1 milliampere.

The henry is quite a large unit, much too large for convenience when considering coils in radio frequency circuits, where we deal with very small voltages, currents and periods of time. The coil in Fig. 4, a typical R.F. coil, is built to have an inductance of .00025 henries—25 hundred-thousandths of a henry. It would be much more convenient to have a smaller unit for use with coils like this so that very small fractions would be unnecessary. So we divide a henry into a million parts, each of which is called a microhenry. Now what would the inductance of our coil be in microhenries? 250 microhenries, of course. And here we have a whole number which is much easier to work with than decimals of five and six places.

Inductances used in audio systems and in power supply systems which are of course parts of the Radio receiver, are considerably larger—some power pack inductances are as large as 50 henries. These coils are wound on iron cores to increase the inductance as we shall see.

Coils are designed to have a certain amount of inductance, depending on the particular circuit in which they are to be used. We shall go on to see what factors determine coil inductance and at the same time learn much about coil design.

CALCULATION OF INDUCTANCE OF R. F. COILS

From what we have already learned about self-induction and mutual induction between turns of a coil, we know that the number of turns must have considerable to do with the inductance of a coil. In fact, the inductance varies as the number of turns vary—the two are proportional. But we must not forget that we have both self-induction, in individual turns and mutual induction between turns, both resulting in inductance, consequently inductance varies directly as the *square* of the number of turns. If we had self-induction only, the inductance would vary *directly* with the number of turns. The same would be true if we had mutual induction between turns only. But when we have both, both must be considered. We have a double effect

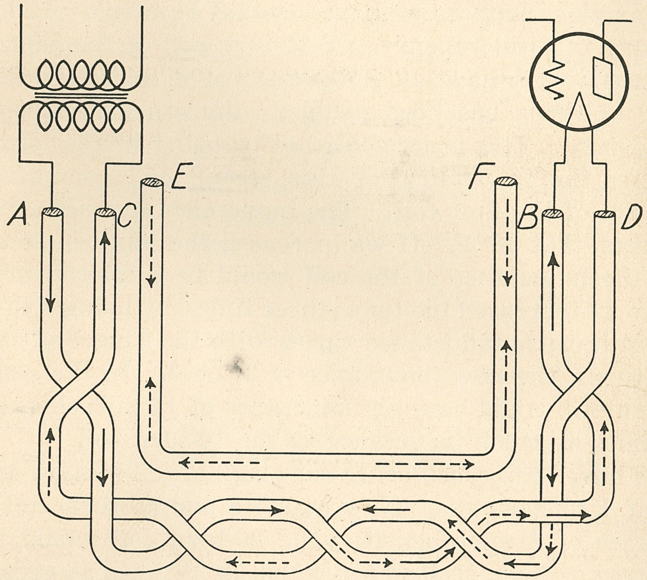


Fig. 9(b)

here, consequently we must consider the number of turns *squared.* This can be stated in symbol form thus:

(1) $$L \propto N^2$$

where L is the inductance of the coil
N is the number of turns

The sign $\propto$ means "varies as" or "is proportional to." N^2 means that the number of turns must be multiplied by itself. From this statement we can see that if the number of turns is increased, the inductance will be increased, or if the number of turns is decreased, the inductance will be decreased.

We can fix this statement in our minds by a simple, practical example. Suppose we have a coil of 10 turns, which has an inductance of 1 microhenry. A 20-turn coil of the same length and shape would have an inductance of 4 microhenries. The number of turns has been doubled—the other dimensions are kept the same. This is accomplished by using smaller sized wire. How does the inductance of this second coil compare to the inductance of the first coil? The inductance has been increased four times, that is, 2^2. If we increased the number of turns to thirty, the inductance of the coil would be 9 microhenries. In this case we increased the turns three times, by using still smaller wire, but because inductance varies with the square of the number of turns, the new inductance is 3^2 or 9. In the same way, a 40-turn coil would have an inductance of 16 microhenries, that is, 4^2 times as much inductance as the 10-turn coil.

We have been considering our original coil to have an inductance of 1 microhenry. Now suppose our 10-turn coil has an inductance of 6 microhenries—the 20-turn coil would have an inductance of 24 microhenries, which is 2^2 times as great as the 10-turn coil. The inductance of a 30-turn coil would be 54 microhenries, of a 60-turn coil, 216 microhenries.

It should be very clear from this that doubling the number of turns does more than double the inductance. Our 60-turn coil has 2^2 times the inductance of the 30-turn coil, not twice the inductance. The 60-turn coil has 9 times the inductance of a 20-turn coil, because 3^2 is 9.

Now what about the diameter of the coil? It would seem that the larger the diameter, the greater would be the inductance, because each turn of wire would be longer in a coil of large diameter, and there would be more self-induction and more

mutual induction between turns. That is exactly what happens, but in making coil calculations we do not consider the diameter, we consider the radius which is just half the diameter and we say that inductance is directly proportional to the square of the radius. This statement stated in symbol form is as follows:

(2) $$L \propto r^2$$

We still have one more dimension—the length of the coil. If we were to say that inductance varies directly with the length of the coil, would you accept it as correct? A little thought on your part would soon show that this statement cannot be true. For a given coil, having a certain number of turns and having a certain diameter, any increase in the length of the coil would necessitate greater spacing between turns. Greater spacing would mean less mutual induction between adjacent turns, and would mean a cutting down of the inductance of the coil. Therefore, inductance is inversely proportional to the length of the coil, which means, as the length increases, the inductance decreases—as the length decreases, the inductance increases. Expressed in symbol form:

(3) $$L \propto \frac{1}{b}$$

In this case we use the symbol "b" to represent length because we use the letter L for inductance. Writing the second half of this statement, "$\frac{1}{b}$" is a simple case of inversion. In statement (2), the r^2 can be considered as $\frac{r^2}{1}$. The symbol "b" alone would be the same as $\frac{b}{1}$. Inverting that, we get $\frac{1}{b}$ and we have an inverse proportionality.

To illustrate this, suppose we have a coil two inches long which has an inductance of 300 microhenries. To double the length of the coil, making it four inches, we would have to double the spacing between turns. The inductance is then 150 microhenries—we have doubled the length but cut the inductance in half.

If the 300 microhenry coil is stretched to four times its length, making it eight inches long, the inductance will be 75 microhenries. Statement 3 explains the number 75. "b" in this case equals 4, and $\frac{1}{4}$ is one-quarter, so the inductance will be one-quarter of 300 microhenries, which is 75 microhenries (μh).

From this it is clear that the inductance of a coil can be changed by simply spacing the turns differently.

All the material in this chapter so far has been intensely practical. Sometimes students write in and say they want to learn Radio, they are not interested learning how to solve problems with pencil and paper. They don't realize that often more can be learned from a simple little problem than from years of unguided experience. For example, a man can build hundreds of coils, and still not know a thing about the inductive properties of those coils. But here, in just a few pages, we have covered all the factors that affect inductance—and these have been made so clear and simple by the use of a few practical examples, that now you have a very clear idea, not only of what inductance is, but about all of the things that must be taken into consideration when designing a simple coil or when calculating the inductance of a coil.

Summing up, inductance is directly proportional to the square of the number of turns, to the square of the radius, and inversely proportional to the length of the coil. All this can be combined in one simple statement:

$$\text{(4)}\quad \text{inductance} \longrightarrow L \propto \frac{\overset{\text{turns}}{N^2} \times r^2}{b} \begin{matrix}\text{Radius}\\ \text{— length}\end{matrix}$$

Let us remember this statement. It tells us exactly what happens to the inductance of a coil when we change the number of turns, the radius or the length of the coil. It also tells us that we can increase the inductance of a coil by increasing the number of turns, or by increasing the radius of the coil, or by decreasing the length of the coil. It is a simple statement of the principles underlying coil design and inductance calculation. To make a "tool" out of this statement, one that we can use for all sorts of coils, we shall have to make a formula of it—that is, we shall have to change this statement so that it will be an equation instead of just a statement of proportionality.

All that is necessary to do this is to multiply one side of the proportion by a "correcting number," a "constant."

The use of constants in formulas is very important and requires some explanation. Let us consider for a moment, a circle with a line drawn through its center, this line being the diameter of the circle. Half of this diameter is the radius of the circle, that is, a line drawn from the center point to any point on the perimeter. If the circumference of the circle is increased, that is, if we make the circle larger, the diameter will be increased also. And the larger we make the circumference, the larger will be the radius. But it is also easy to see that the circumference is not equal to the radius—the two are proportional, but never equal. Our statement of proportion would be:

$$C \propto r$$

How can we make an equation of this statement? Mathematicians long ago discovered that the circumference of a circle is equal to $2\pi r$ where π is 3.1416, and r is the radius. Thus the difference between the equation, $C = 2\pi r$ and the statement of proportionality, is the constant 2π, which is used to multiply the second half of the statement. Now both sides are equal and we have a true equation.

The constant 2π is so-called because it applies to any circle—it never changes, it is *constant*. Peculiarly enough, this relationship between the radius and the circumference of the circle is met with all throughout mathematics and all sciences and the symbol π* is seen in a great many formulas which seem far removed from any connection with a circle. It is a most valuable constant for scientific purposes.

Now we want to make an equation out of the statement in 4, so that we can substitute numerical values for the symbols and make actual computations for a given coil. The complete formula for inductance is:

$$\text{(5)}\ \underset{\mu H}{\overset{\text{Ind.}}{\text{in}}} \text{—} L = \frac{\overset{\text{turns, radius}}{N^2 \times r^2} \times K}{10 \times b} \begin{matrix}\text{constant}\\ \text{— length}\end{matrix}$$

---

*In Radio it is customary to consider "π" as 3.142 or simply 3.14 for most calculations. Engineers usually follow this rule in making practical calculations—of numbers beginning with 1, 2 or 3, only the first three or four places are significant. Thus 2.74836 would be written 2.748 or even 2.75. Of numbers beginning with 4 to 9, only the first 3 places are significant—70,499,213 would be written 70,500,000.

where L = inductance, in microhenries
N = number of turns
r = radius of the coil, in inches
K = a constant, found from table 1
b = length of the coil in inches

We must use the number 10 in the denominator because the radius of the coil and the length of the coil are given in inches. If these were given in centimeters we should have to use another constant.

To find the value of K, divide the diameter by the length of the coil, then from table No. 1 obtain the number to be used in the formula. Suppose you divide the diameter by the length and you get ½ as the result. In the left-hand column of the table you look up 0.50 and you find that the value of K is 0.8181 and this is the number you substitute for K in this particular case.

In order to fix in our minds the formula and the use of the table, let us take a concrete example and work it out. Let us say the coil whose inductance we want to calculate has 84 turns of No. 24 D.S.C. wire, its diameter is 2 inches and its length is approximately 2 inches—for No. 24 D.S.C. wire can be wound approximately 41 turns per linear inch.

To find a value for K, we divide the diameter by the length. Each is 2 inches and 2 ÷ 2 = 1. Then we refer to table No. 1 and in the first column, "Diameter over Length," we notice to the right of Fig. 1 in the next column under "K" the fraction .6884. This then is the numeral which must be employed for a coil of this length and diameter.

Substituting values for letters in the formula, we get:

$$L = \frac{1^2 \times 82^2 \times .6884}{10 \times 2}$$

Simplifying this, we have:

$$L = \frac{1 \times 6724 \times .688^*}{20} = \frac{6724}{20} \times .688 = 336.2 \times .688 = 231 \ \mu h$$

The result is slightly more than 231 microhenries but this is close enough for all practical purposes.†

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*Notice that the number begins with 6, so we use only 3 significant numbers.

†The answer should have another number, but the whole calculations were made roughly so 231 is near enough.

TABLE NO. 1

VALUES OF K FOR USE IN SELF-INDUCTANCE FORMULA

Diameter / Length	K	Diameter / Length	K
0.00	1.0000	1.75	0.5579
.05	.9791	1.80	.5511
.10	.9588	1.85	.5444
.15	.9391	1.90	.5379
.20	.9201	1.95	.5316
0.25	0.9016	2.00	0.5255
.30	.8838	2.10	.5137
.35	.8665	2.20	.5025
.40	.8499	2.30	.4918
.45	.8337	2.40	.4816
0.50	0.8181	2.50	0.4719
.55	.8031	2.60	.4626
.60	.7885	2.70	.4537
.65	.7745	2.80	.4452
.70	.7609	2.90	.4370
0.75	0.7478	3.00	0.4292
.80	.7351	3.10	.4217
.85	.7228	3.20	.4145
.90	.7110	3.30	.4075
.95	.6995	3.40	.4008
1.00	0.6884	3.50	0.3944
1.05	.6777	3.60	.3882
1.10	.6673	3.70	.3822
1.15	.6573	3.80	.3764
1.20	.6475	3.90	.3708
1.25	0.6381	4.00	0.3654
1.30	.6290	4.10	.3602
1.35	.6201	4.20	.3551
1.40	.6115	4.30	.3502
1.45	.6031	4.40	.3455
1.50	0.5950	4.50	0.3409
1.55	.5871	4.60	.3364
1.60	.5795	4.70	.3321
1.65	.5721	4.80	.3279
1.70	.5649	4.90	.3238

By this time I am sure you understand inductance calculation thoroughly. Knowing just this one equation and how to use it, you can calculate the inductance for any single layer air core coil such as you will find in any Radio circuit.

INDUCTIVE REACTANCE

In all the experiments we have performed so far with coils, we used a source of D.C. voltage. We could see the effect of inductance in a circuit very clearly if we were to place a coil having considerable inductance in series with an electric light bulb, in a 110-volt D.C. circuit, as in Fig. 10. Turning the current on we notice that the light does not glow with full brilliance instantly—the inductance of the coil momentarily hinders the flow of current. But after this momentary sluggishness, the lamp will glow with its usual brilliancy, just as though the inductance were not in the circuit. Upon breaking the circuit, we should notice a large spark at the switch contact, the result of the magnetic field about the coil returning its energy to the circuit in the form of a back e.m.f.

Now we want to see what will happen if we place our coil in an A.C. circuit. And we are chiefly interested in this because in Radio, the R.F. coils are used in radio frequency circuits, which are of course A.C. circuits. We change the circuit shown in Fig. 10 merely by changing the source of e.m.f.—we connect our coil and lamp to an A.C. source. See Fig. 11. Turning on the current, we find that the lamp is very dim, much dimmer than it would be without the inductance in the circuit. From this we can gather that the current is not flowing through the coil readily and that the inductance is affecting the current flow.

During the first period, the first half cycle, of the alternating current flow, the action of the inductance is exactly the same as when direct current is made to start and stop in an inductive circuit. Even after the applied voltage has swung to zero, current continues to flow in the same direction as the original current, according to Lenz's Law. This current is the current flow induced by the collapsing magnetic field about the coil. Now we are interested in knowing what happens during the second period when the current flow reverses its direction.

It isn't at all difficult to realize that the e.m.f. of the second period will be opposed by the induced e.m.f. of the previous period. And so with every following period—each will be opposed by the induced e.m.f. of the previous period. Therefore we say that the induced e.m.f. reacts (acts back) on the original current. This reaction hinders the flow of current. The greater the inductance, the greater will be this reaction.

Inductance therefore reacts on the A.C. current flowing through a coil in such a way that the current is decreased. And this property of inductance is called inductive reactance (always X_L).

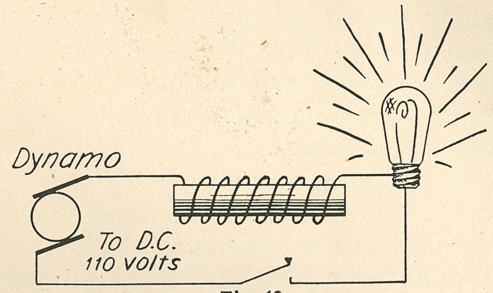


Fig. 10

Now the question uppermost in your mind is: "What is the difference between reactance and resistance, as both limit current flow?" There is one important difference that we can mention here—others we must keep until later. You remember that when a resistance is used to cut down current flow, a certain amount of energy is lost in heat. But no energy is lost in a coil—energy is merely stored in the coil's magnetic field and when the field is caused to become smaller or collapse, this energy is returned to the circuit. No energy is lost at all. Of course it must be remembered that this applies only to A.C. circuits—for limiting direct current flow, resistance is the only means at our disposal.

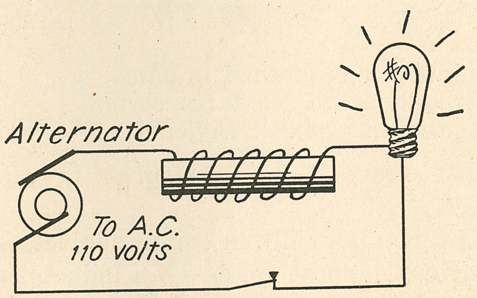


Fig. 11

Coming back to inductive reactance, it is obvious that the greater the inductance, the greater the inductive reactance will be. This makes possible another statement of proportionality.

(6) $$X_L \propto L$$

But A.C. current has frequency, as you well know. If the frequency is low, say 60 cycles per second, the inductive reactance will be small, because the flux will expand and collapse slowly thus inducing only a small back e.m.f. in the coil turns. If, however, the frequency is increased, the flux will have to move faster, and cutting the turns faster will induce in them a correspondingly larger e.m.f. Thus inductive reactance is proportional to frequency and our statement is:

(7) $$X_L \propto f$$

We can combine our two "statements of proportion" and we have:

(8) $$X_L \propto f \times L$$

To change this statement to an equation, we must multiply the second part by a constant, which in this case is 2π (2×3.14). The equation is then:

(9) $$X_L = 2\pi f L$$

where X_L = inductive reactance, in *ohms.*
f = frequency, in cycles per second.
L = inductance of coil, in henries.

Notice that reactance is measured in ohms, just like resistance.

To fix this formula firmly in our minds, let us take another practical example. Suppose we have an inductance of 5 henries in an alternating current circuit and that the frequency of the A.C. current is 60 cycles per second. Making substitutions in our formula we get:

$$X_L = 6.28 \times 60 \times 5 = 1884$$

As reactance is always expressed in ohms, in this case the reactance of the coil to A.C. current flow in the above example is practically 1885 ohms.

What will happen if we increase the frequency? Let us say that in our previous example we increased the frequency from 60 to 1000 cycles per second. Then:

$$X_L = 6.28 \times 1000 \times 5 = 31{,}400 \text{ ohms}$$

From which it is clear that as frequency goes up, reactance goes up considerably.

THE EFFECT OF INDUCTANCE ON PHASE

In the previous lesson you were introduced to the subject of phase and phase relations. It was brought out then that several variations of phase were possible—that voltage and current could be "in phase" in which case current reaches maximum at the same time voltage reaches maximum. In some circuits, current will lead voltage, in others, current will lag behind voltage. From what you know about the effects of inductance in a circuit it won't be difficult to figure out the phase relations between voltage and current in an inductive circuit. We can go back to our D.C. experiment, the one shown in Fig. 10. You'll remember that when we turned on the current, the lamp did not glow normally immediately—there was a period of time during which the current was building up to maximum. But the instant we closed the circuit, the voltage was maximum. Therefore it is obvious that current lags behind voltage in inductive circuits.

Figure 12 illustrates this effect very nicely. The rise in current (AB) requires a definite period (AC). If it were not for the opposing voltage, the induced back e.m.f., the current would rise immediately to its maximum value and line AB would be a straight vertical line rather than a sloping curve.

The curve to the right of Fig. 12 (DF) shows how the inductance affects current when the source of e.m.f. is removed. Notice that it is just the reverse of the starting current curve, showing that when the source of e.m.f. is disconnected from the circuit, the current tends to keep on flowing for the same length of time it took the current to build up to maximum at the start.

Another way of describing this effect of inductance on phase, is to say that voltage leads current. We can follow through several cycles of alternating current in an inductive circuit, and then we will never forget that inductance in a circuit causes the current to lag behind the voltage, or what is the same thing, the voltage to lead the current.

The instant current starts flowing through the coil, a voltage is induced in the coil opposing the flow of current, tending to hold it back. Because of this induced voltage, the applied current reaches maximum after the applied voltage reaches maximum. And the applied voltage is zero before the current reaches zero. The same is true for each succeeding cycle.

In an inductive circuit, the voltage leads the current by almost a quarter of a cycle. For convenience, a cycle is divided into 360 equal periods, each of which is called a degree. In other words, for convenience we consider a cycle, a circle. A quarter of a cycle will be 90° (ninety degrees). Therefore in a purely inductive circuit, current and voltage 90° out of phase—voltage is 90° ahead of current. This is brought out clearly in Fig. 13.

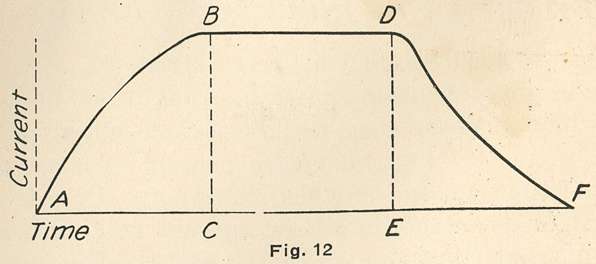


Fig. 12

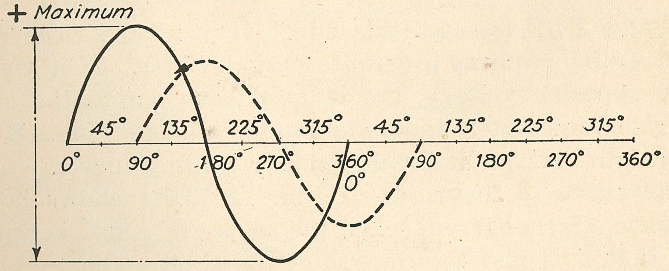


Fig. 13

The effect of resistance in an inductive circuit is to decrease the angle of lag. The curve shown in Fig. 13 is really an ideal curve, impossible in practice because we cannot have a circuit or a coil without resistance.

Figure 14 shows current lagging behind voltage 45°, due to resistance in the circuit. Bear in mind that the lag may be any angle between 0 and 90 degrees depending on the resistance in the circuit, that is, the resistance of the coil and any resistance in series with the coil.

Attention → In a circuit containing only resistance there would be no phase difference and the curve would appear as in Fig. 15.

INDUCTANCE IN THE RADIO RECEIVER

The uses of inductance in a Radio receiver are many as a glance at the circuit diagram in Fig. 16 will convince you. Let us start right at the antenna and go through the circuit, examining each inductance so we can become acquainted with the various uses of inductance coils in Radio receivers.

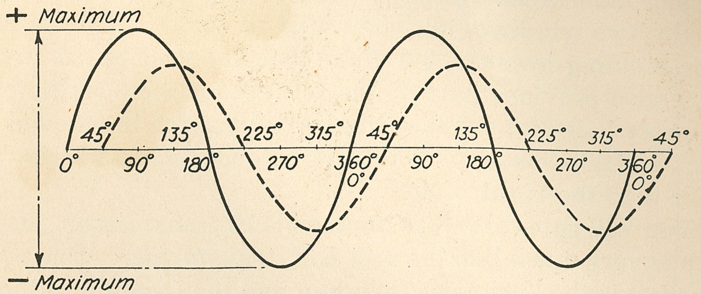


Fig. 14

The first inductance we see is marked by the figure 2 in a circle. Notice that there are two coils. They make up what is known as an R.F. transformer which is nothing more than a means of passing energy from one circuit to another by mutual induction, the magnetic effect which you have gotten to know so well in this lesson. But in this case we have mutual induction between coils instead of between conductors. And about mutual induction between coils you will learn much more in a later lesson.

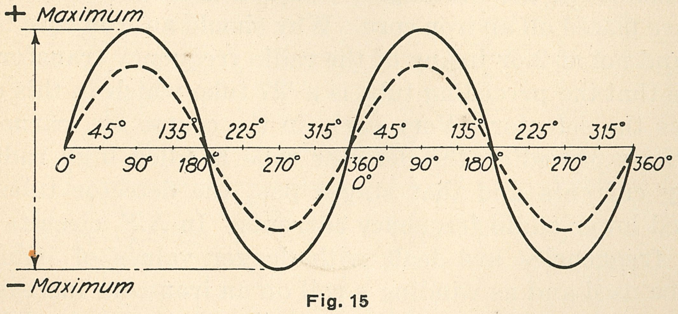


Fig. 15

Although R.F. transformers are shown in the diagram separated in two parts, most R.F. transformer windings are placed on the same framework which is cardboard or bakelite tubing.

The coil or winding shown to the right has a second function—it supplies inductance for the first tuning circuit. Tuning circuits will also be taken up in detail in later lessons.

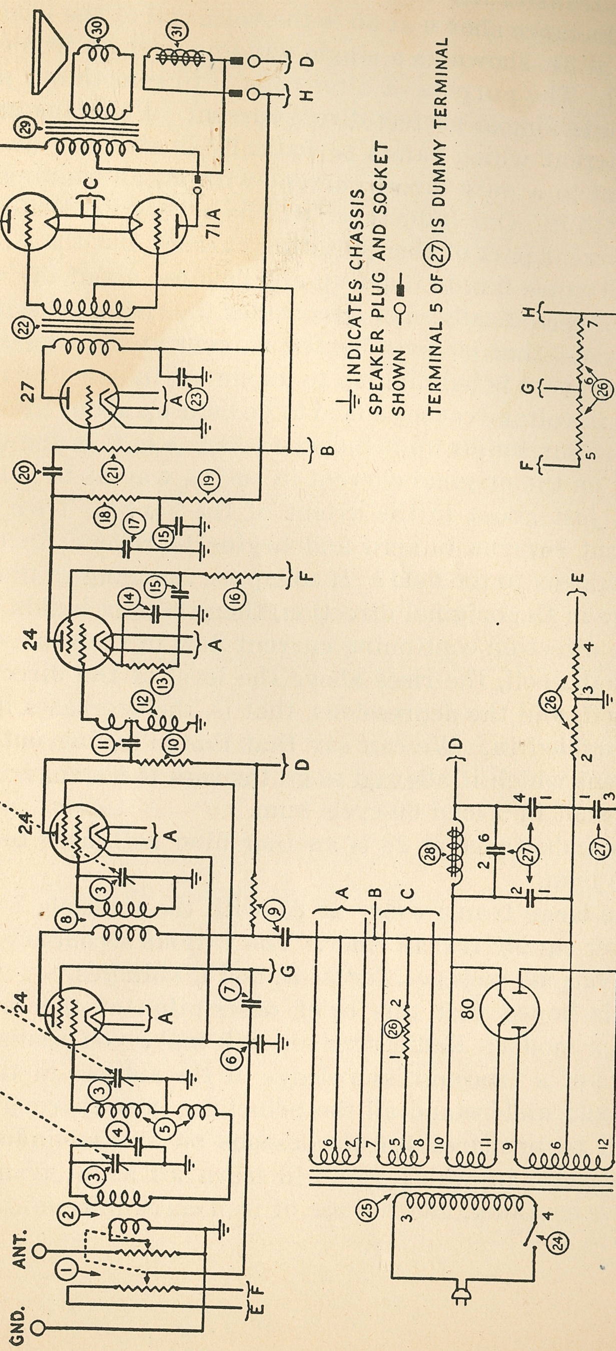
The inductance marked 5 is the second R.F. coil. In this case the two windings are connected in series. The lower half of the winding is connected directly to the first tuned circuit so that it also provides part of the total inductance of the circuit. The upper half of 5 supplies the inductance for the second tuned circuit which is made up of this inductance and the variable condenser 3 to the right of it.

You will recognize 8 as another R.F. transformer, the third, which is very much like the first R.F. transformer. The winding on the left is the "primary" winding and the winding to the right is the "secondary" winding. The secondary winding in this case provides the inductance for the third tuned circuit.

At 12 we have still another R.F. transformer. However, in this case neither of the windings is in a tuned circuit.

Now we do not see our symbol for inductance, which by this time we are very familiar with, until we reach No. 22. And here we have something new—notice the three lines drawn between the symbols for the windings. These lines mean that the windings are placed on an iron core. Why should an iron core be used here and not at 2 or in any of the radio frequency transformers? Notice that the preceding tube is a '27 tube which in this case is used as the detector. Very early in the course we learned that the stages preceding the detector tube handled high radio frequency currents and that stages past the detector tube stage handled lower audio frequency currents. In A.F. circuits where lower frequencies are dealt with, larger values of inductance must be used and as winding a coil on an iron core increases the inductance considerably, iron core coils are always used in A.F. circuits. The effect of an iron core is to provide a better path for the flux—for magnetic lines of force travel through iron with much greater ease than through air. You will learn much more about iron core coils in later lessons.

This brief description of an audio frequency transformer is merely to act as an introduction to the subject. We shall study these, too, in great detail later in the course.



ANT.
GND.
71A
71A
27
24
24
24
80
A
B
C
D
E
F
G
H
INDICATES CHASSIS
SPEAKER PLUG AND SOCKET SHOWN —○■—
TERMINAL 5 OF (27) IS DUMMY TERMINAL

Fig. 16—Circuit diagram of a typical broadcast receiver with its power supply circuits.

The transformer at 29 is another A.F. transformer. The small inductance shown at 30 is the voice coil of the loudspeaker. The coil at 31, shown as a single winding over an iron core, is a filter coil. The purpose of filter coils is to smooth out pulsating current into almost perfect direct current. Pulsating current is direct current which varies periodically in strength and thus is equivalent to a pure direct current with an alternating current mixed with it. Our inductance will have very little effect on the direct current part of this pulsating current, but the A.C. variations will cause flux to build up and collapse about the windings of the coil periodically. Let us consider the rising cycle of pulsating current—that is, consider the current at the time when the A.C. component is building up to maximum in one direction. The increase in voltage causes a field to be built up about the windings but as the flux builds up it induces a back e.m.f. in the windings, reacting on the original current in such a way as to hold it back slightly, just about to the extent of the surge. Then the A.C. component returns to zero and begins to reverse in direction. What happens to the field? It collapses, inducing in the winding a voltage in the original direction, then the flux builds up in the opposite direction continuing current flow in the same direction. Thus in the coil, the rises above the level of the direct current are cut off, and the depressions, that is, the decreases in current flow, are filled in. We can say that this is taking out the A.C. component which if allowed to go through the speaker windings would result in a loud 60-cycle hum.

The inductance at 28 is another filter coil, used to filter out 60-cycle hum.

The large transformer at 25 with the multiple winding, is the power supply transformer. The various secondary windings are for various voltages, for A, B, and C voltages.

It is hoped that this brief description of the inductances used in a modern Radio receiver will make you realize the importance of a thorough knowledge of the subject of this lesson. You should understand all the principles in it thoroughly—then you will be prepared for the lessons on mutual induction and transformers, in which you will learn all about transformers, inductive coupling, and the use of iron cores in coils.

TEST QUESTIONS

Number Your Answer Sheet 6FR and add Your Student Number.

Never hold up one set of lesson answers until you have another set ready to send in. Send each lesson in by itself before you start on the next lesson.

In that way we will be able to work together much more closely, you'll get more out of your course, and better lesson service.

1. Why is inductance often called "electrical inertia?"
2. Why does a coil of wire have much more inductance than a straight wire?
3. In what section or sections of a Radio receiver might a .00025 henry (250 microhenry) air core coil be found?
4. What effect on the inductance of a coil would spacing its turns farther apart have?

look in discussion sheet →

5. What would be the value of "K" to be used in the inductance formula, for a coil three inches long and having a diameter of two inches? ← decimal
6. How can electrical energy be transferred from one circuit to another even though there is no direct connection between them?
7. What two effects does inductance have on alternating current?
8. Name three uses to which inductance coils are put in a Radio receiver.
9. Explain the principle of non-inductive winding.
10. What would be the phase difference between voltage and current in an inductive circuit which contained no resistance?

note P. 25?